**Department of Electrical and Computer Engineering**
**The Robotics Institute**

# Metrology Systems Perspective on Micro/Nano Devices

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*NIST Workshop on Metrology Needs for Micro/Nano-Technology*

*September 21, 2005*

# MEMS Metrology

- **Dimensions**
    - **displacements, modes**
    - **widths, gaps**
    - **sidewalls, underwalls**
    - **roughness**
    - **curling, shape**
- **Material properties**
    - $E$, $\nu$
    - **stress, stress gradients**
    - **density**
    - **damping**
    - **thermal properties**
    - **active properties**

- **Tribology**
    - **Friction, Stiction**
    - **Creep**
    - **Wear**
    - **Fatigue**
        - **static / dynamic**
- **Yield**
    - **defects**
    - **faults**
- **Variation**
    - **temperature**
    - **die to die variation**
    - **run to run variation**
    - **aging**
    - **packaging**
    - **ambient**

# MEMS Design Flow
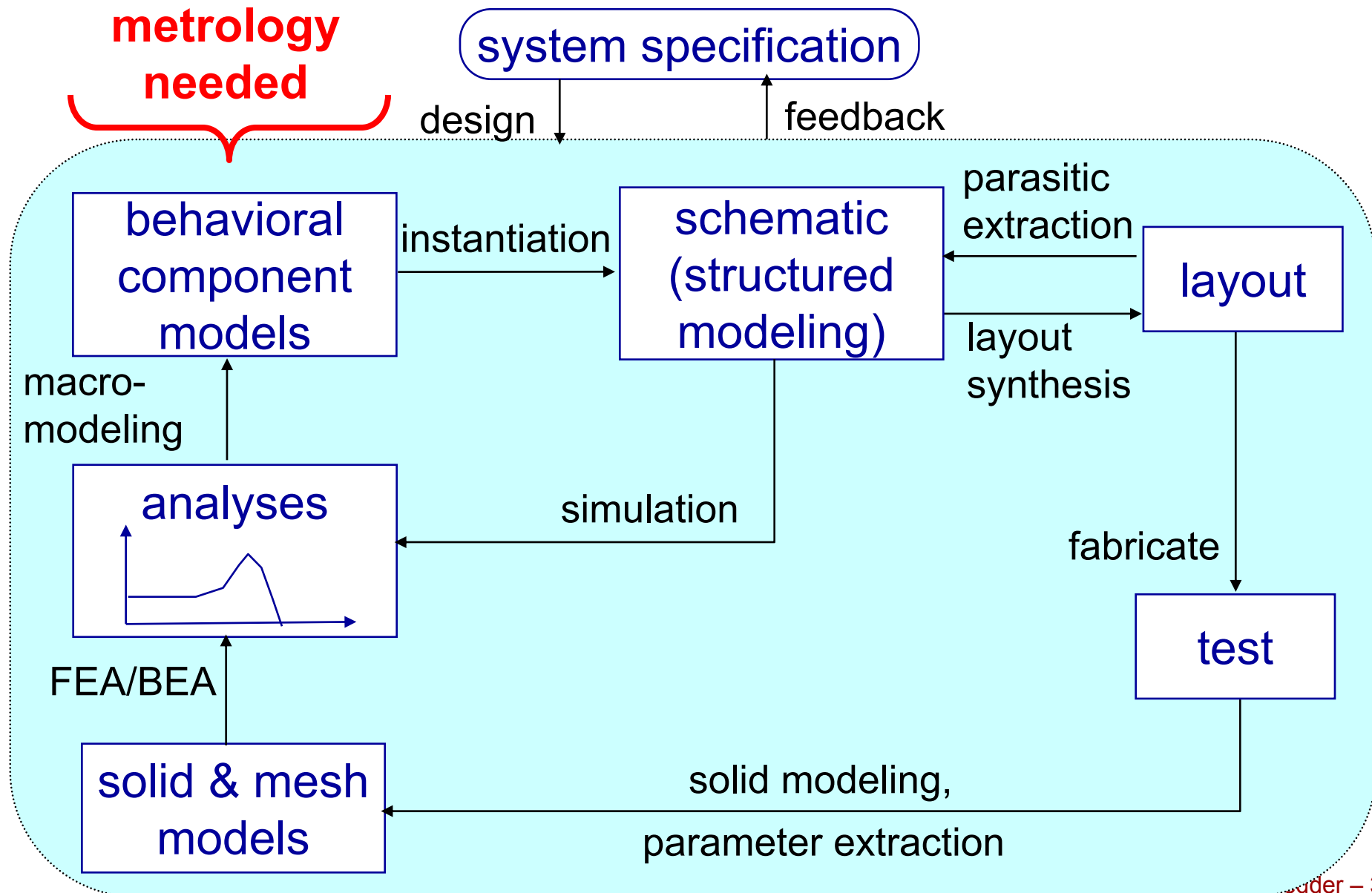
# MEMS Circuit Schematic

- **Schematic composition of behavioral models**
- **Tools:**
    - **MEMSCAP's MEMSPro**
    - **Coventor's ARCHITECT**
    - **UC Berkeley's SUGAR**
    - **Carnegie Mellon's NODAS**
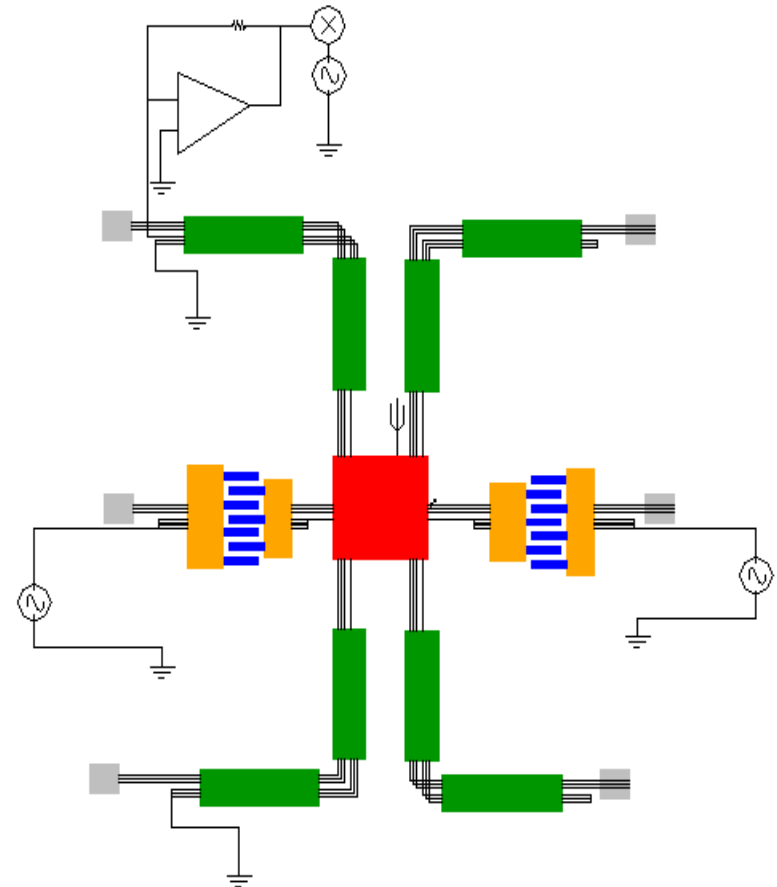
# MEMS Design Testbed Vision

- **Driven by MEMS Schematic/Simulation Design Tools**
- ■

- **Flow A) MEMS metrology system**
  - **Extract structure (size and defects)**
  - **Generate solid model and mesh**
  - **Back annotate to MEMS schematic**

- **Flow B) MEMS Automated Testbed**
  - **Design and simulate microstructures**
  - **Download testbed configuration to Microvision system**
  - **Compare simulated and measured results**

# Automated Testbed Data Flow

*Process material properties:*
*E, $\rho$, TCE, thickness, $\sigma$*

*Stimulus,*
*outputs*

**Test equipment**

**Microvision system**

*Extracted geometry*

**x-y drive**

*Layout, nodes*

*simulation*
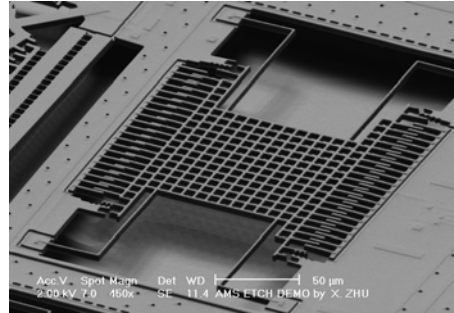
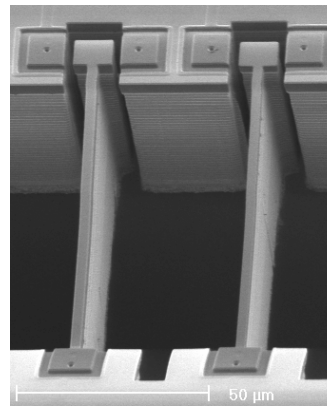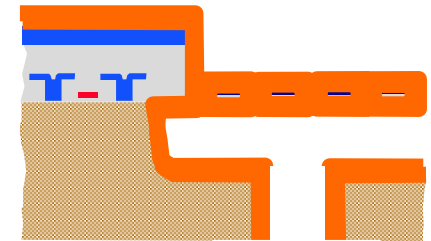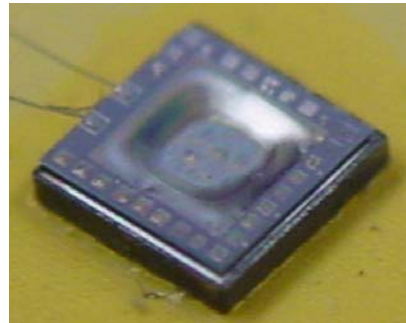**Image registration**

*measurements*





G. K. Fedder
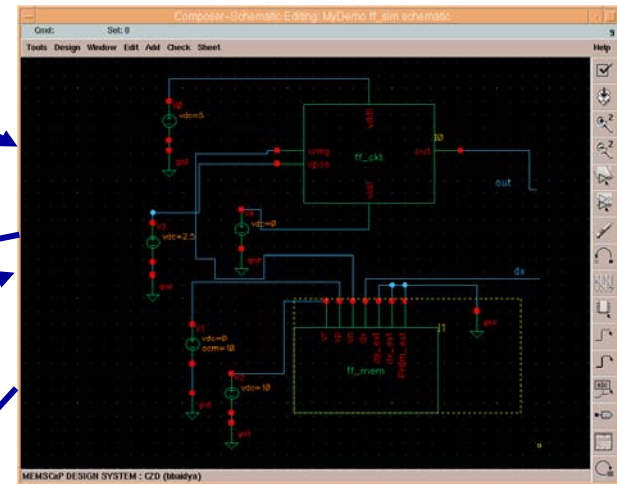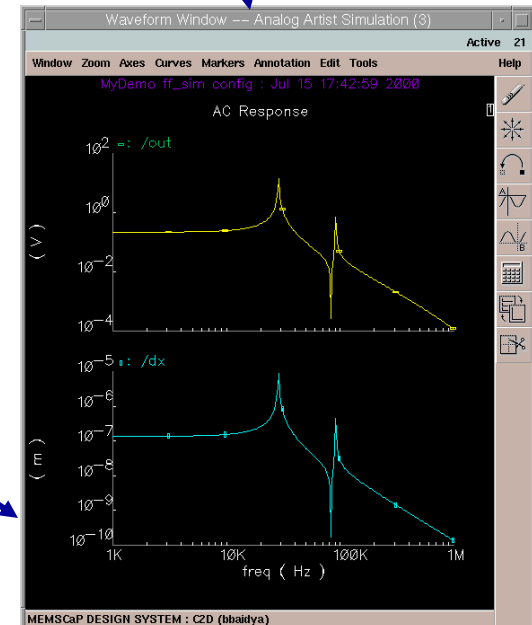
# CMOS-MEMS Technologies

- **Foundry process technology base**
  - **Highly integrated microsystem platforms**
  - **But, MEMS material properties are not quantified**
- **Questions always asked:**
  - **How reliable?**
  - **What is variation to "X"?**
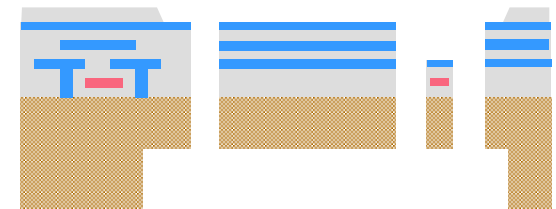- **Requires LOTS of samples and measurements**
  - **time, effort and $**

**Thin-Film CMOS-MEMS**
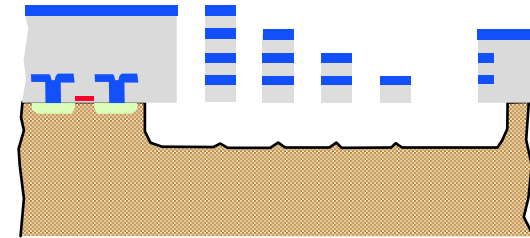


**Membrane CMOS-MEMS**



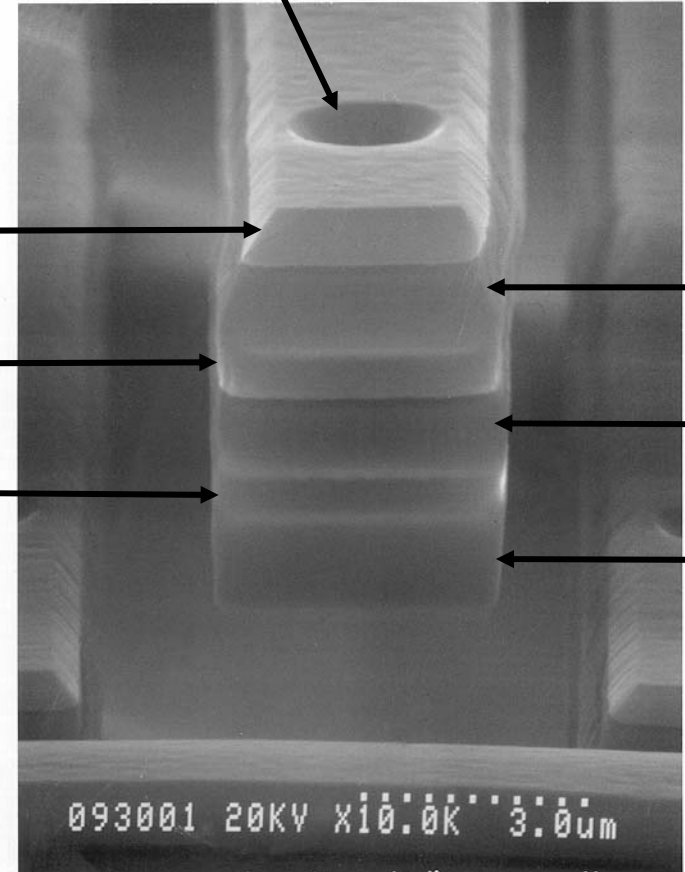**DRIE Si CMOS-MEMS**

# Geometry Example: CMOS MEMS Beams

- **Top metal is exposed and thinned by ion milling**

- **Underlying metal layers may be exposed, depending on layout**

**Via from Metal-3 to Metal-2**

**Metal-3**

**Metal-2**

**Metal-1**

093001 20KV X10.0K 3.0um

**Oxide layers**

# Process & DRC Test Structures

**CMOS-MEMS Plate**

**Si undercut**

Plate with no Holes Undercut Test
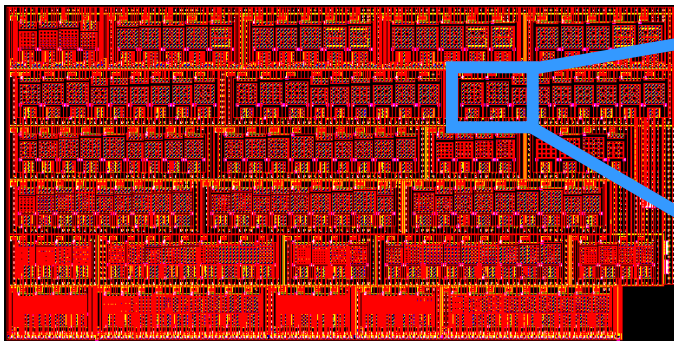
Plate With Holes Release DRC
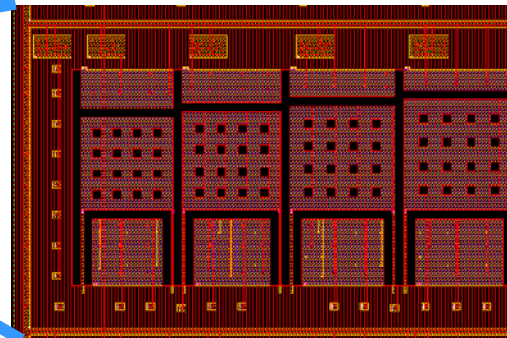
6 $\mu$m gap
6 $\mu$m x 6 $\mu$m holes
{60.5, 64.5, 68.5,
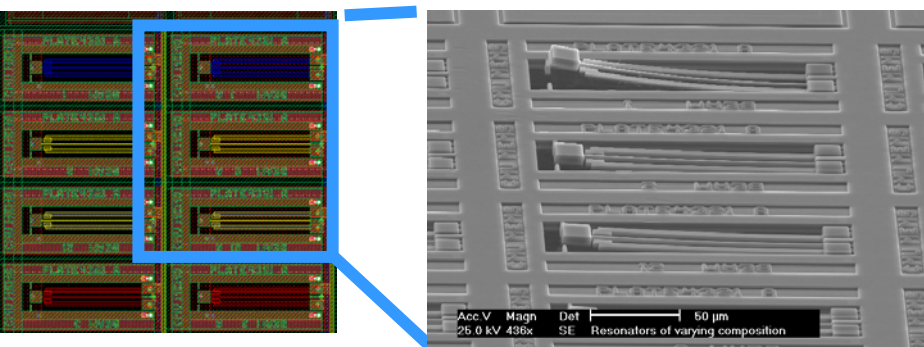 72.5} $\mu$m plate width
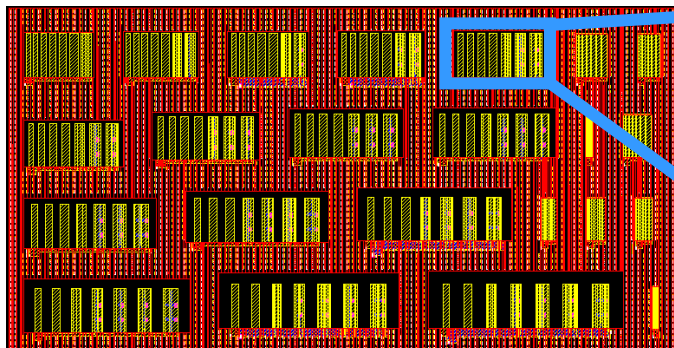
Beam Release DRC
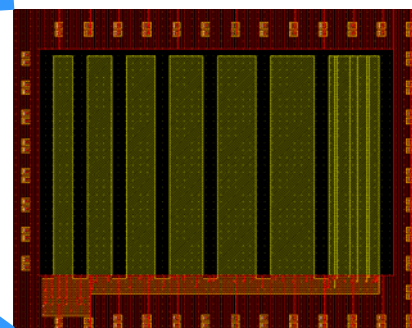
10 $\mu$m gap
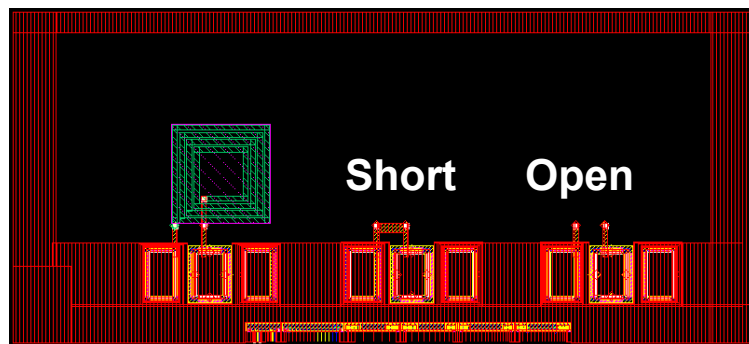{13.0, 16.6, 19.5, 22.5,
26.3, 30.0, 34.2} $\mu$m
beam widths

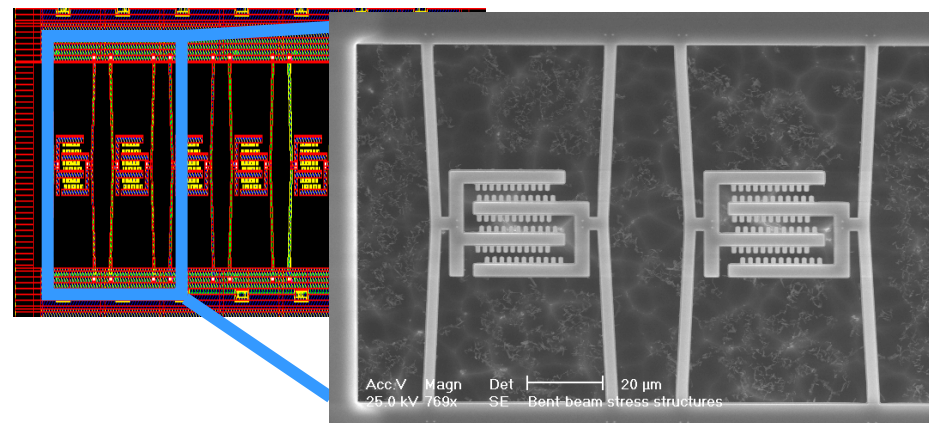# Material & Device Test Structures

Mechanical properties:

**Axial Stress**

**Beam Resonator
Length 125 μm
Plate 15 μm x 15 μm**

Capacitive interfaces:

**Output Buffer
Amp**

RF-MEMS passives:

**Short     Open**

**Inductor**
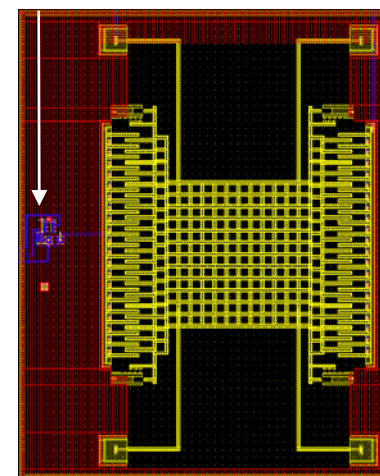
**Crab-leg Resonator**

# M-TEST  P.M. Osterberg, S.D. Senturia, JMEMS '97

- **Pull-in of cantilevers, fixed beams and diaphragms**
- **Electrical test to extract E and tensile σ**
- **Challenge to generalize and be accurate**
- **e.g., compressive σ, stress gradients, support compliance, substrate curvature**
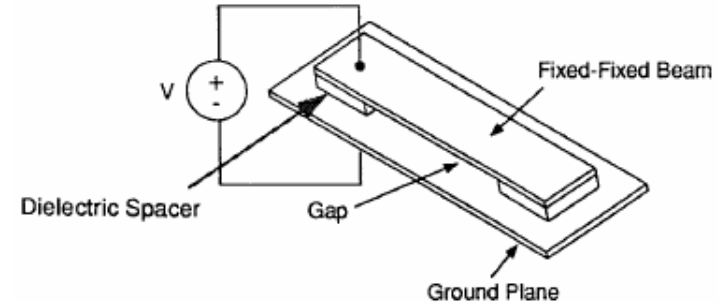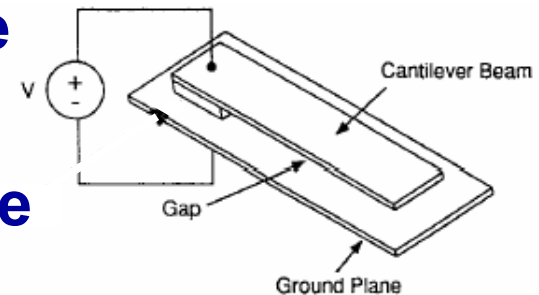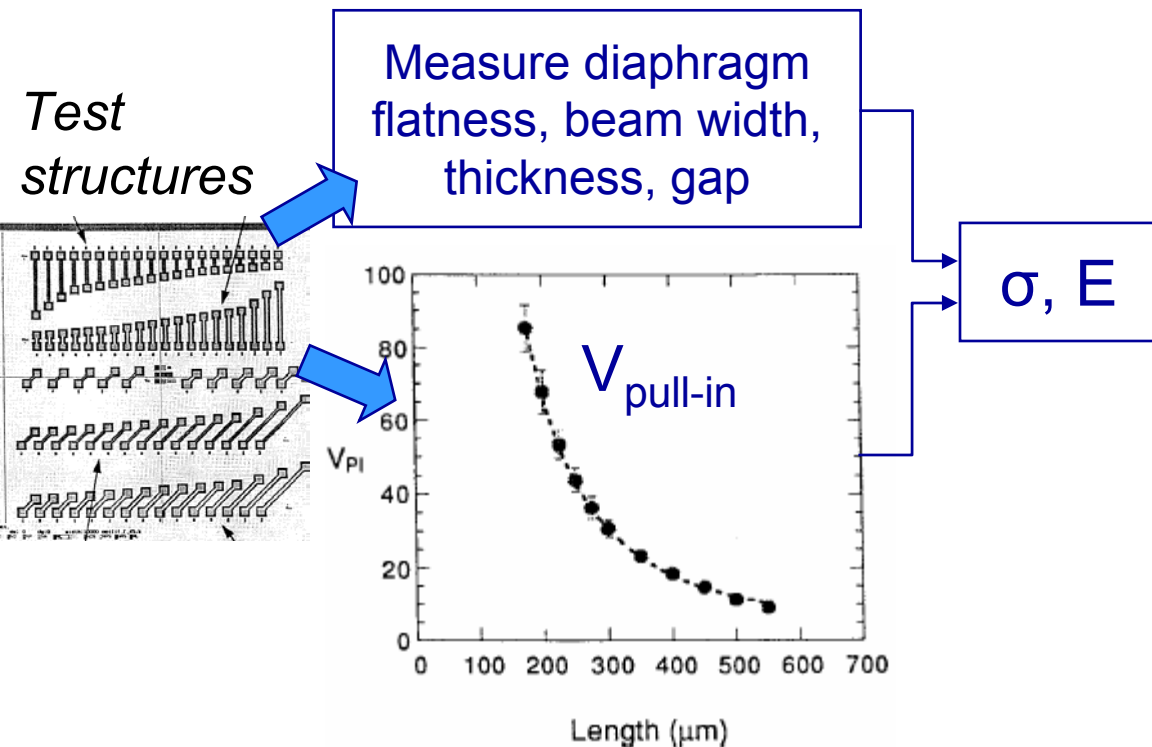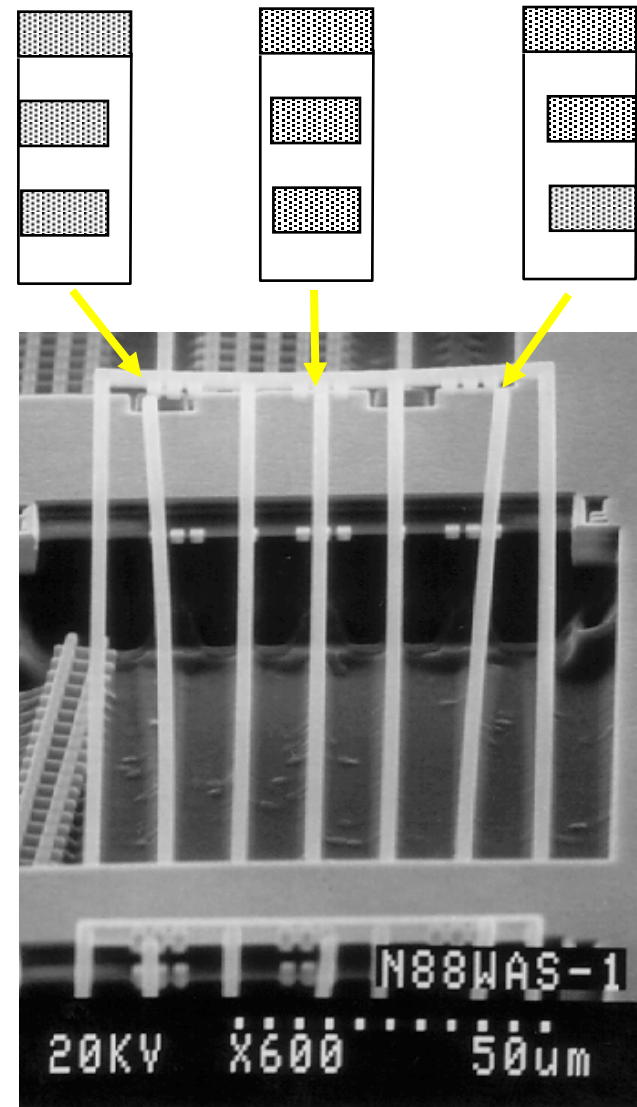
*Test structures*

Measure diaphragm flatness, beam width, thickness, gap

$V_{pull-in}$

σ, E
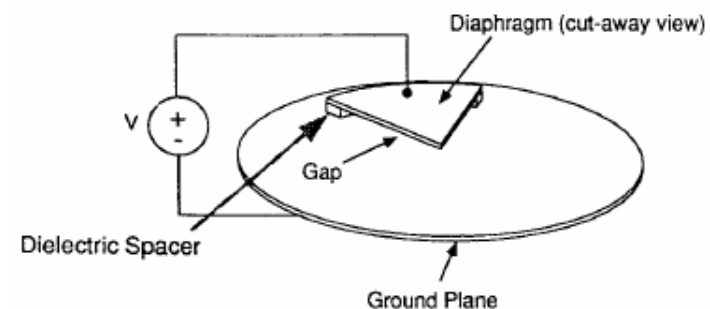
# Lateral Curl Example

- **Metal offset creates lateral stress gradient**
- **Direction of curl depends on CMOS misalignment**
- **SEM shown is Agilent 0.5 μm CMOS**
  - **100 μm-long, 1.2 μm-wide beams**
  - **0.3 μm offsets of metal-2 and metal-1 with respect to metal-3**



20KV    X600    50μm

# Actuator Operation

- **Stiff actuators made with beams in parallel (e.g. 5 beams)**
- **40 × 200 μm² actuator provides up to 25 μm stroke (7.5 mW) and 1.2 ms response**

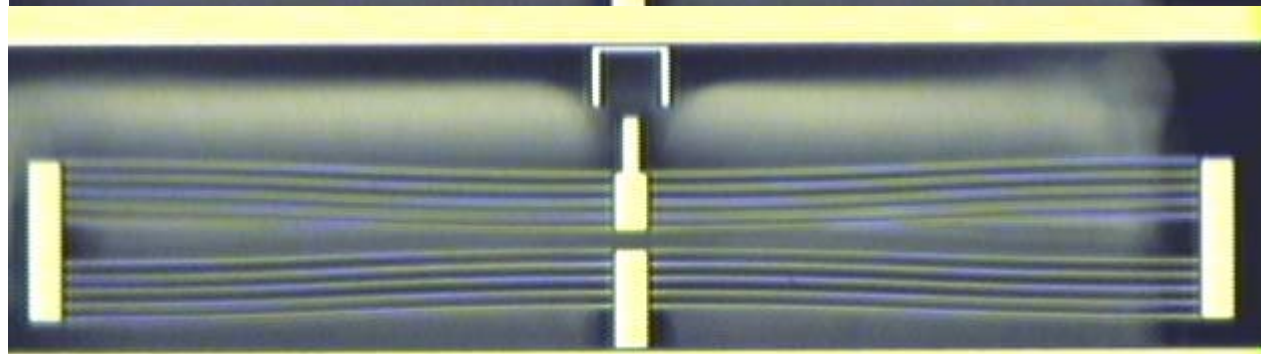*single-ended folded-flexure*
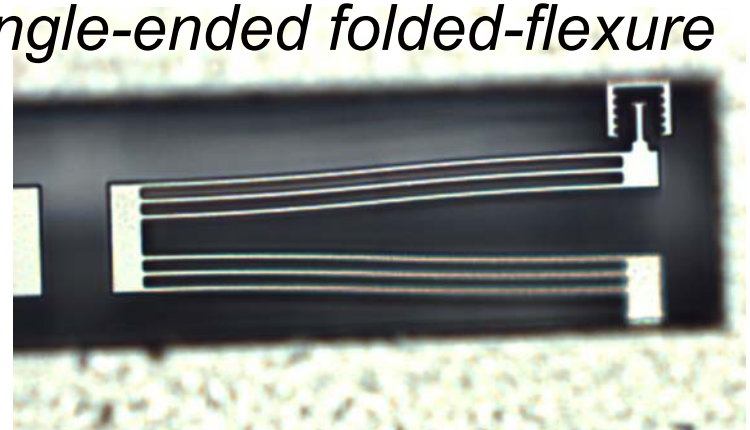


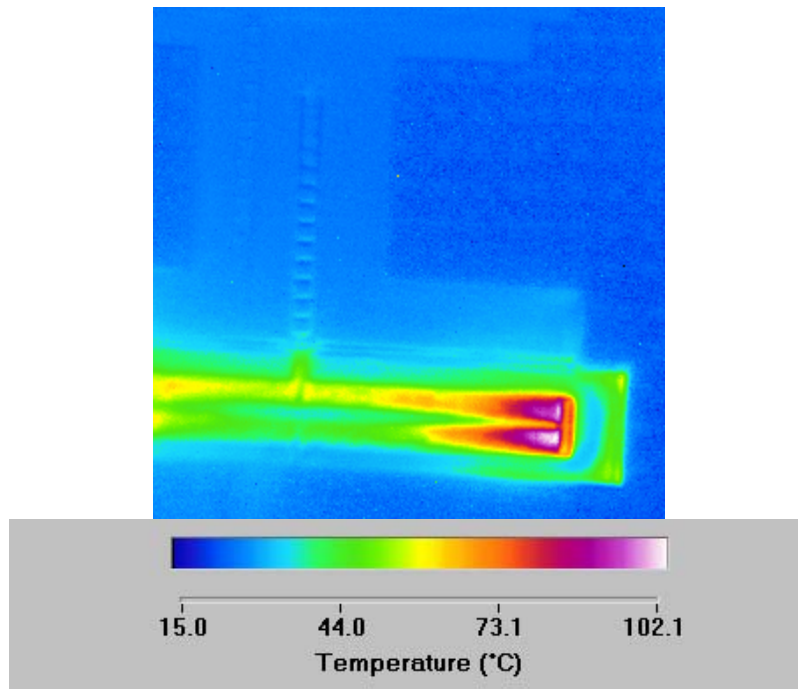*symmetric folded-flexure*

200 μm

10 μm self actuation

(25°C)

40 μm
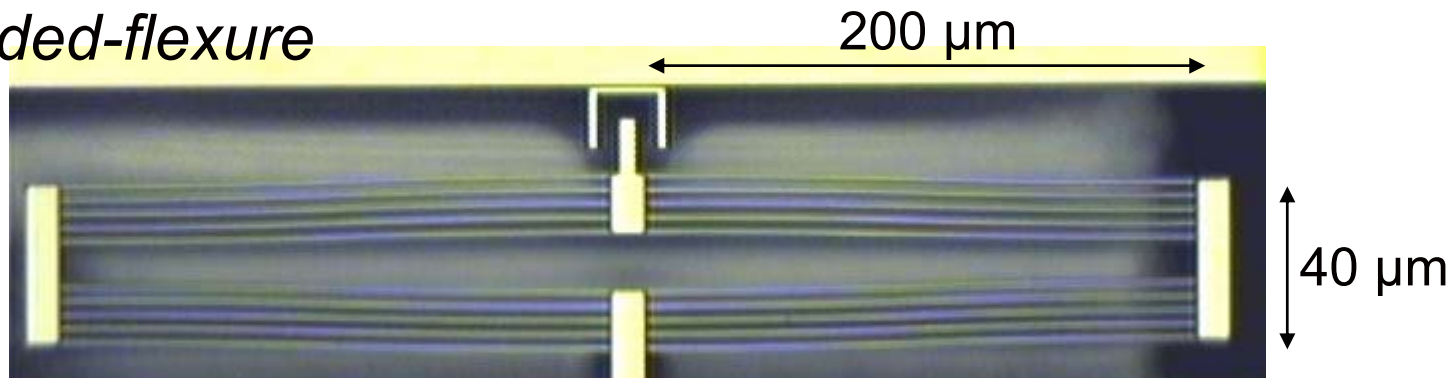
20 μm electrothermal actuation

(178°C)

# Electrothermal Lateral Actuator (Temperature Distribution)

*Measurement:*

*Simulation:*



maximum T = 375K
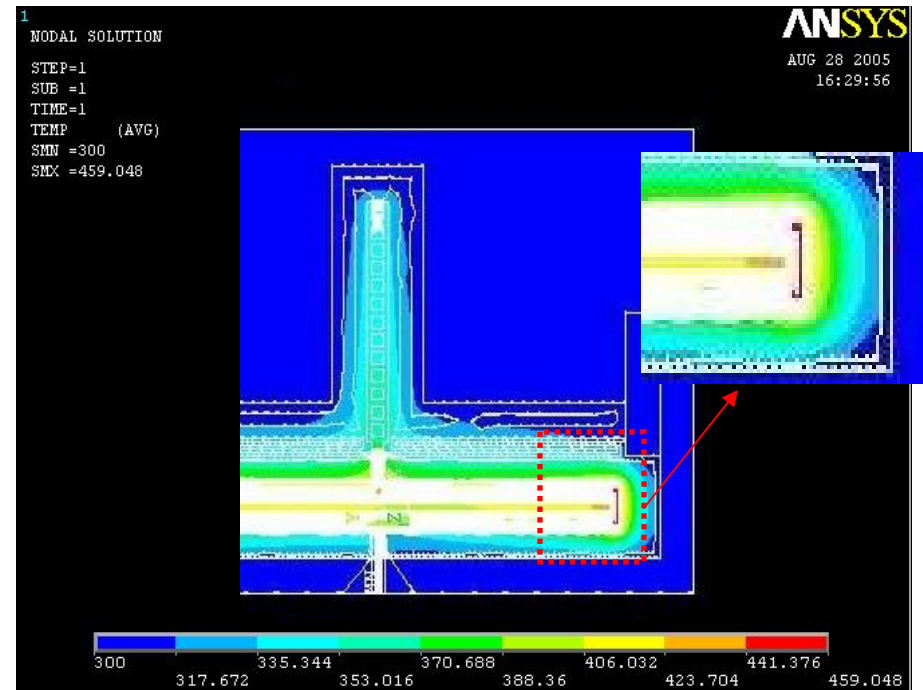
maximum T = 459K

- *Driving voltage = 2.5V*
- *Background temperature is set to 300K*

# Cyclic Fatigue

- **"Notch" structure first presented by Failure Analysis Associates and MIT**
- **Studies few and far between..**
- **Dependent on ambient**

polysilicon example:





C. Muhlstein et al, Tribology Issues and Opportunities for MEMS, B.Bhushan, 1997
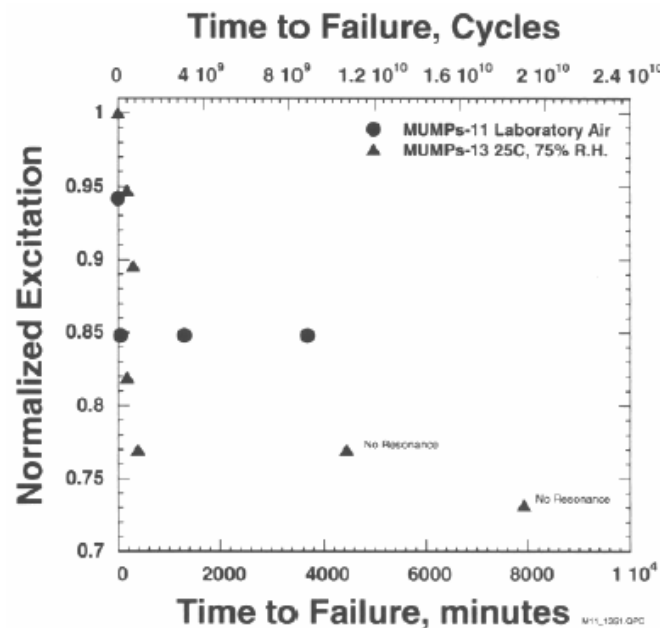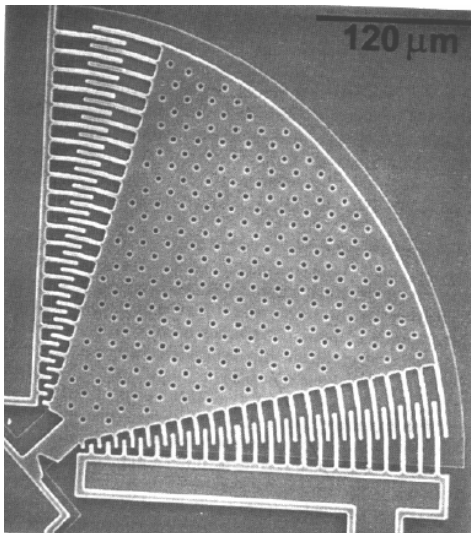
CMOS-MEMS accelerated fatigue example,
M. Lu et al, MRS, 1998
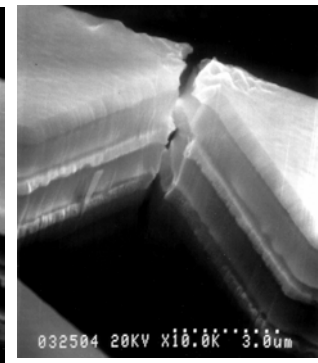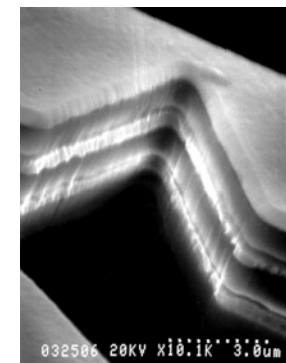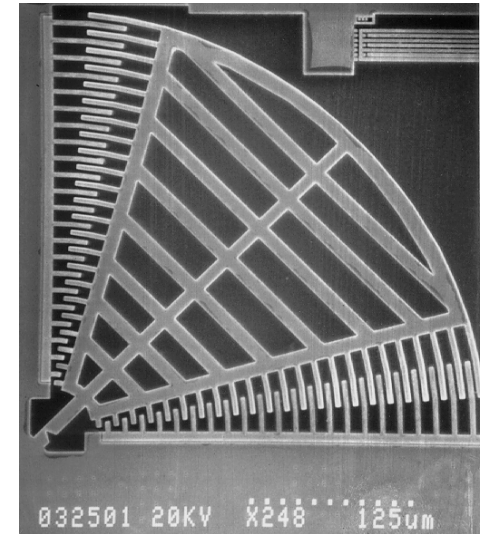




4.5 million cycles, 10 µm stroke, 620 MPa

# Material Property Changes with Fatigue

- **Polysilicon grain dilatation with cyclic stress**
- **Two-peak resonant frequency profile with time**
- **Aged structures stabilize faster**





AFM observation of clamped ends of the actuated beams

AFM observation of the impact zone (beam/dielectric interface)

O. Millet et al, MEMS 05
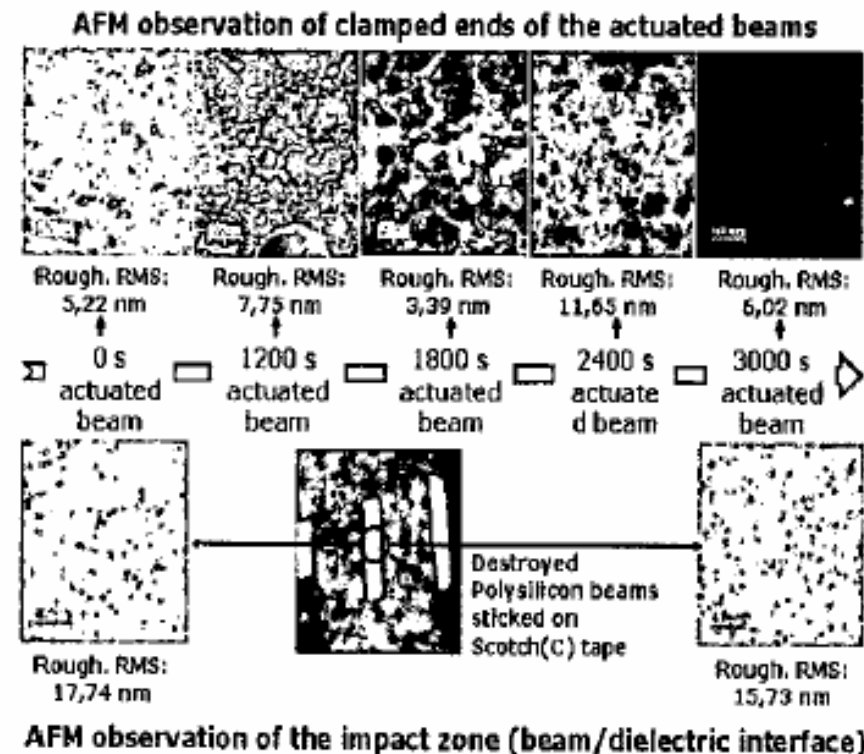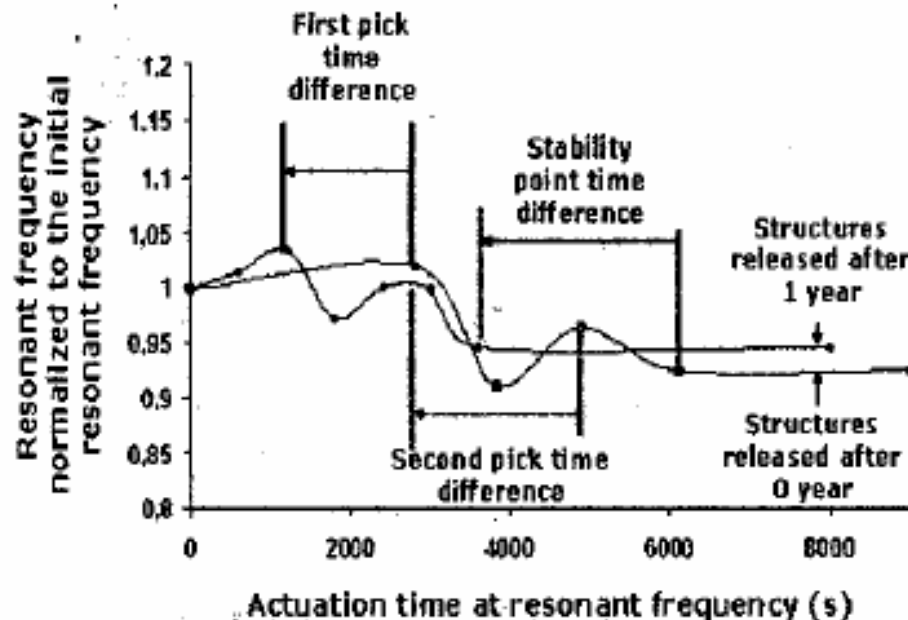
# MEMS Fault Testing  *R.D. Blanton, Carnegie Mellon*

- **Specification-Base Test for MEMS Defects Insufficient**

*ADI accelerometer example*



**Defect and variation overlap**

**acceptability range from manufacturing variation**

<span style="color:red">defect exists but is not detected!</span>

Resonant frequency $f_0$ (Hz)

Particle location

# Accelerometer Built-In Self-Test (BIST)

*R.D. Blanton,*
*Carnegie Mellon*

## ■ Multi-mode actuation to identify faults



$x$
$y$

$v_{1,1}$
$v_{3,1}$
$V_1$  $V_4$  $V_2$  $V_3$
$V_1$
$c_{1,1}$
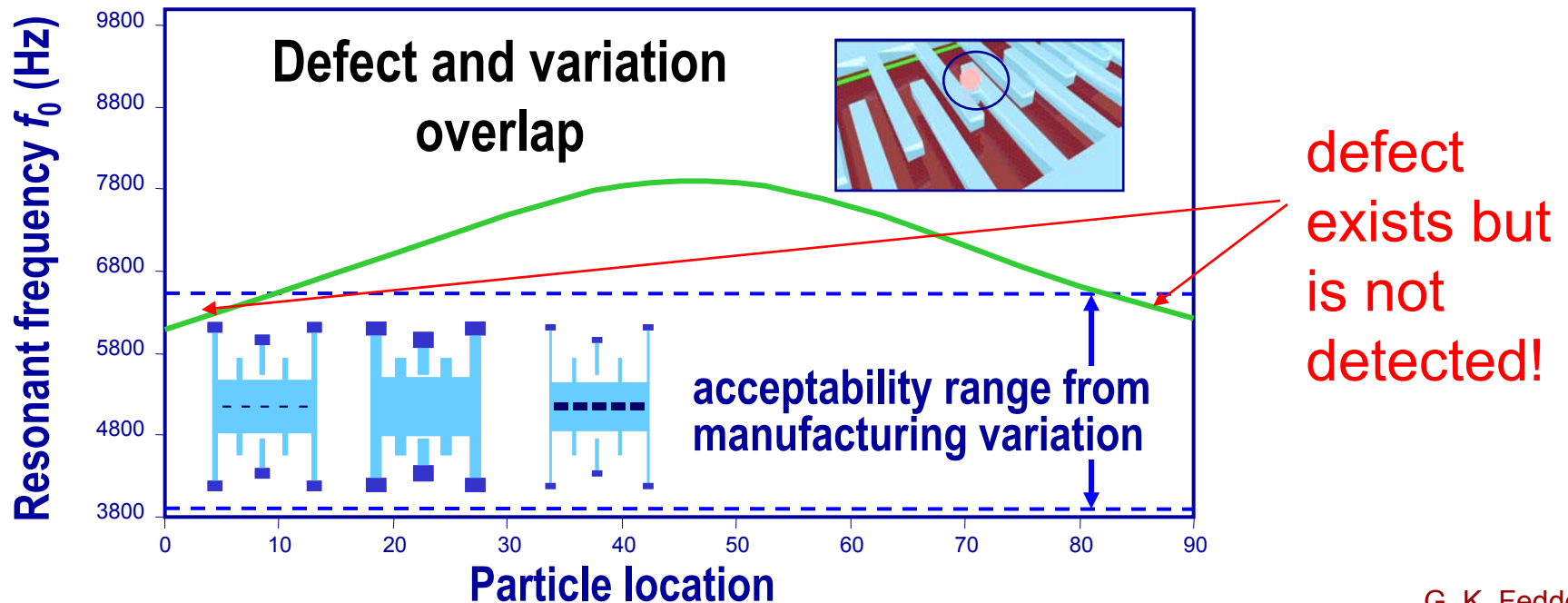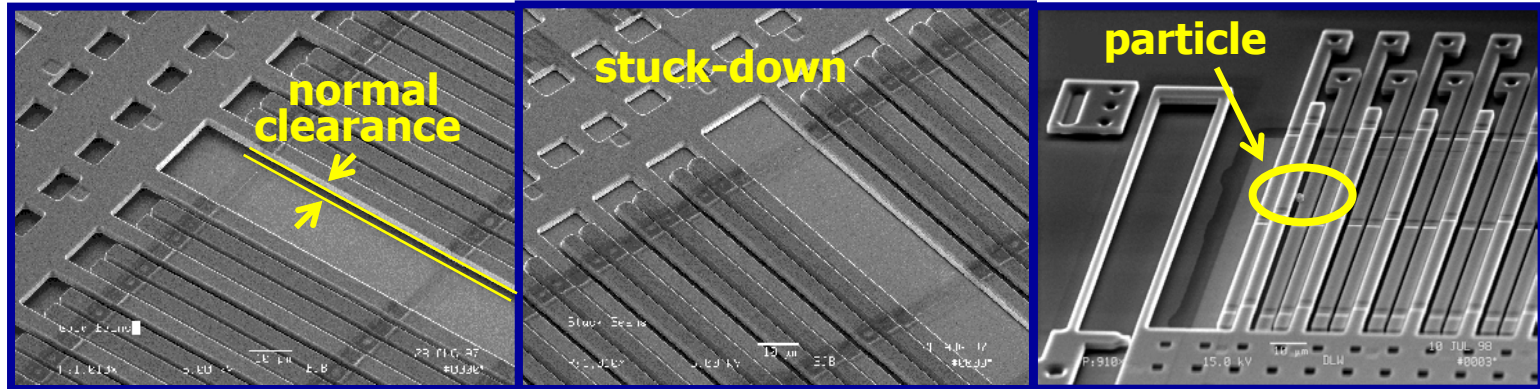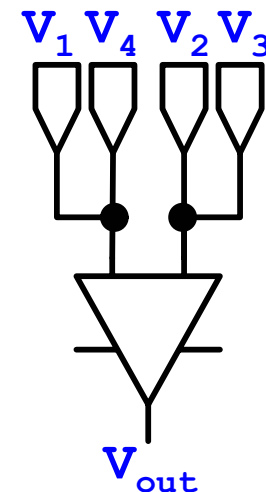$c_{3,1}$
$V_3$
$v_{1,2}$
$c_{1,2}$
$c_{3,2}$
$v_{3,2}$
$v_{2,1}$
$c_{2,1}$
$c_{4,1}$
$v_{4,1}$
$V_2$
$V_4$
$c_{2,2}$
$c_{4,2}$
$v_{2,2}$
$v_{4,2}$
$V_{out}$
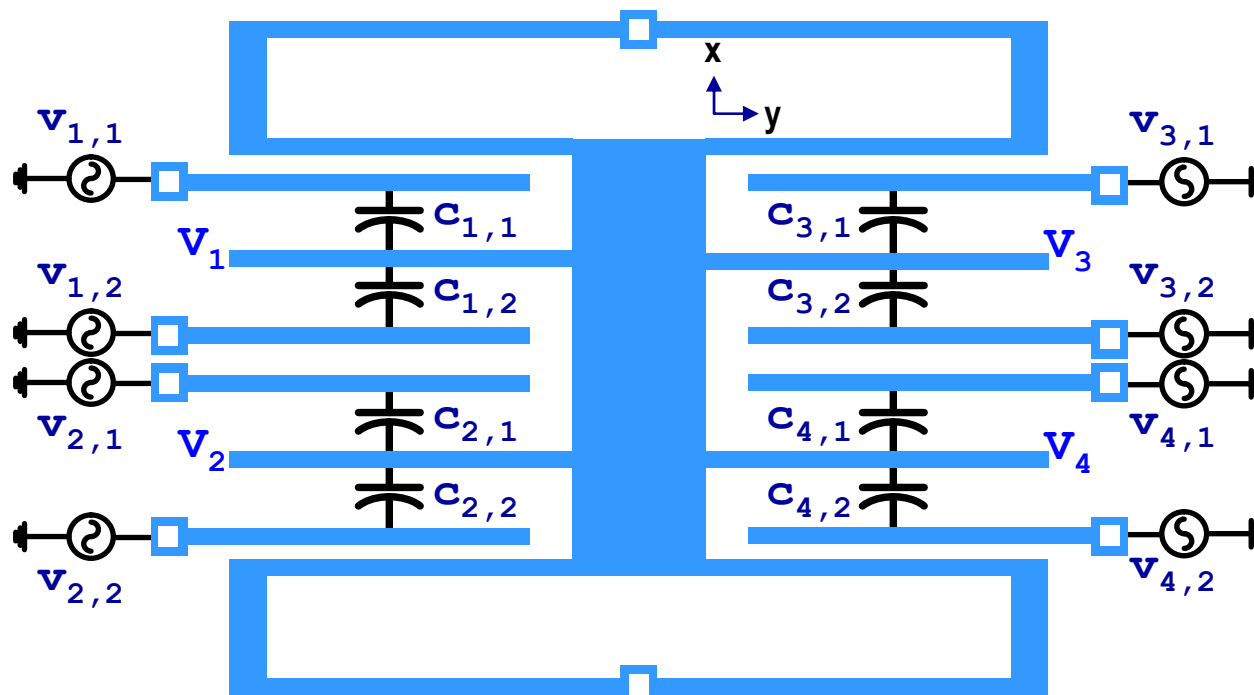
**pos:** $V_{i,1}=V^+$ ; $V_{i,2}=V^-$

**neg:** $V_{i,1}=V^-$ ; $V_{i,2}=V^+$

| Normal | 1:pos 4:pos 2:neg 3:neg |
|--------|-------------------------|
| X mode | 1:pos 4:neg 2:neg 3:pos |
| Y mode | 1:pos 4:neg 2:pos 3:neg |
| X and Y | 1:pos 4:pos 2:pos 3:pos |

**X mode**

Voltage output (µV)

Defect location as percentage of finger length
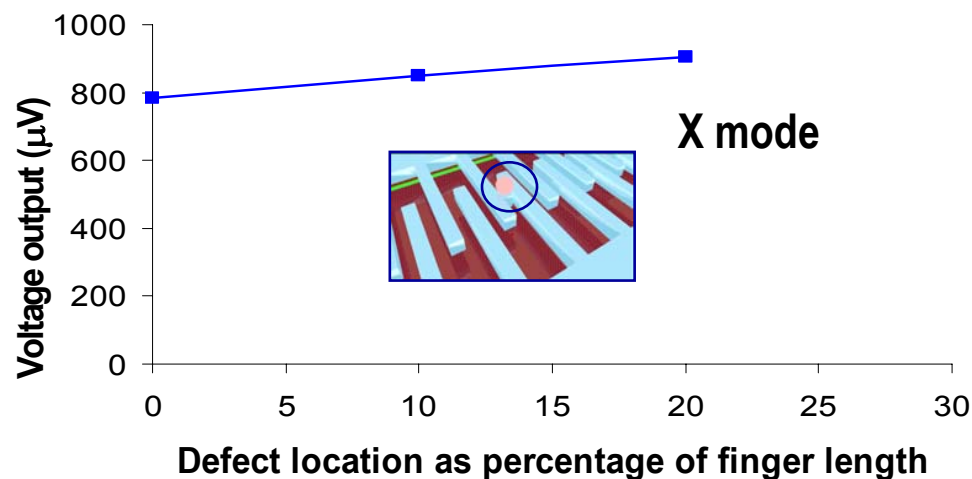
# The Case for Built-In Self-Test (or "Self-Assessment")

- **BIST is needed for defect detection and diagnosis**
- **BIST however can also be used in the field during the lifetime of the design as a "reliability" watchdog or checker**
- **BIST also can be used for process characterization in the context of the given system**
  - **standard test structures *lack* the geometric richness that you find in real designs**
  - **using BIST measures along with appropriate model(s), allows one to keep track of the process over time with very fine granularity**

# Conclusions

- **Great need for more automated metrology tools and techniques**
  - **Analysis of variation, faults and reliability require lots of testing**
- **Mechanisms should be employed to encode best practices and design knowledge**
  - **e.g. test structures with analysis equations**
  - **widely adopted, not proprietary**
- **Future may lead to more built-in self-test in production MNT systems**